RISK-RETURN ASSESSMENT OF IRRIGATION DECISIONS IN HUMID REGIONS

W. G. Boggess, G. D. Lynne, J. W. Jones, and D. P. Swaney

The environment for decision-making at the farm-firm level has always been volatile, but particularly so in recent years. Product prices have seen wide fluctuations, due in part to a reduced emphasis on farm-price support programs and more reliance on world markets. Input prices, especially those that are energy related (fertilizers, chemicals, fuels), have also increased in an erratic manner in recent years. Changes in the basic institutional setting, including farm-price support policy, water supply regulation, environmental controls, and trade policy have all contributed to variability. As a result, it has become even more important to better understand the nature of risk and uncertainty-reducing processes, such as irrigation.

There are many sources of variability affecting irrigation management. The purpose of this paper is to show what these sources are and how to include them in an analysis, and to suggest the implications for choice of an optimal irrigation strategy within a humid region, such as the Southeast. We use a time-dynamic soybean-yield simulation model to generate the production estimates and other simulators to generate cost estimates. Historical weather and price information provide the data sources which ''drive'' the simulators.

REVIEW OF LITERATURE

The irrigation manager is faced with the intricacies in the soil-water-atmosphere-plant realm as well as the complexity of the socio-political-legal-institutional-economic setting in which production is planned and implemented. This problem setting has been addressed by researchers from many disciplines. The following literature review is a comprehensive attempt to provide the reader with a means for judging the context for the present study. All the irrigation strategy analyses reported in recent professional (not just economic) journals were reviewed to determine: (1) what specific objectives were ascribed to the irrigation manager and (2) how the variability issue has been addressed. These two dimensions were selected because they are fundamental in providing a perspective on this literature.

Objectives of Irrigation Managers

Amir et al. provides some insight into the overall dilemma faced by the researcher interested in defining ''optimal'' irrigation strategies in their statement that, ''every farmer has his own experience and preferences which can hardly be formulated in mathematical terms'' (p. 1413). This perspective may be correct, although some inroads have been made with utility analysis (English and Orlob). Amir et al. suggest the development of interactive, computer scheduling models enabling the user to execute a ''decisive role in directing the search (for a strategy) according to his preferences,'' which relieves the researcher from specifying a well-defined objective function. A case can be made for this view; however, there are situations where specifying the choice criterion can be useful, especially as it relates to making general recommendations or formulating water-use policy. Nearly all researchers have chosen this latter approach.

Most of the literature visualizes a decision-maker having a single-dimensional objective, such as to maximize unconstrained yield (Anderson and Maass; Ahmed and van Bavel; Dean; DeBoer et al., Fangmeir and Mohammed; Harrington and Heerman; Jackson and Ferguson; Lambert et al.; Morey and Gilley; Stegman et al.) or unconstrained profit (Anderson, Jay et al.; Boggess et al.; Burt and Stauber; English et al. 1981; Gowon et al.; Hart et al., Lembke and Jones; Morgan et al.; Van Deman et al.; Windsor and Chow). Others have added various conditions or provisos. Dylla et al. attempted to minimize nitrate percolation and drought stress subject to a constraint of maximum yield. Hall and Buras; Dudley et al.; Hall and Butcher; and Harris and Mapp suggested maximization of profit, subject to a water constraint. Wu and Liang chose to minimize irrigation cost, and Schoney et al. minimized water consumption and energy costs, subject to maximum yield. Other objectives (which usually give the same end result) are to maximize evapotranspiration (ET), while minimizing applications of water, fertilizer, and pesticides (Hammond et al. 1981), or to ''conserve'' water, while avoiding yield loss (Rhoades et al.). Prihar et al. chose to reduce the irrigation-water/pan-evaporation ratio while Trava et al. recommended

W. G. Boggess is an Assistant Professor and G. D. Lynne is an Associate Professor of Food and Resource Economics, University of Florida. J. W. Jones is a Professor and D. P. Swaney is a Research Associate, Department of Agricultural Engineering, University of Florida.

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minimizing irrigation labor costs, subject to maximizing yield (no crop stress). Howell and Hiler suggested that maximizing yield subject to a water constraint may be appropriate from the perspective of a water-use planner, but for the individual irrigation manager, maximizing yield is "seldom desirable from an economic viewpoint" (p. 873). Heerman et al. recognized that some producers are interested in maximizing yields, while others wish to minimize irrigation and fertilizer costs, subject to varying constraints on profits and/or yields. The irrigation-scheduling service started in the Western U.S. by the USDA-ARS (Jensen and Wright) is often used under the assumption that yield is to be maximized, as the goal is to achieve more efficient water use without reducing yields. However, Jensen et al. (1970) counsel that increased net returns are necessary to motivate farmers to change from "traditionally accepted scheduling methods" (p. 26) to those provided by USDA-ARS service, suggesting that profit maximization may be a more appropriate goal.

As expected, there has been a definite tendency for the economists contributing to the irrigation-strategy literature to offer the profit maximization model as most appropriate. Other scientists (agricultural and civil engineers, agronomists, soil scientists) usually suggest the maximum yield goal. Both will yield the same answer, of course, only if the production function is linear.[1] Stewart and Hagan (p. 429) note, that crop production functions related to field water supply will nearly always be nonlinear. However, this also allows that some *will be* linear, which insures that profit and yield maximum rules give identical results. Also, what are the goals of "real life" irrigation managers? Interestingly, there was no evidence in the literature that the actual behavioral dimensions of these managers had been explored.

Variability and Irrigation in Risk Reduction

Variability is all pervasive within this decision environment, which manifests itself in at least five different and somewhat separable ways:

1. aboveground conditions, such as those relating to plant capabilities, manner of soil cultivation, level of weed control, wind conditions, degree of solar radiation, rainfall quantity and timing, humidity and temperature.
2. belowground conditions, including rooting depth and density, nutrient movements and levels, water holding and hydraulic features of the soil, proximity to ground water, and infiltration rates.
3. product price variability, as perceived through each season as harvest approaches and over several seasons in sequence. The institutional setting for marketing the products is also a variable here.
4. marginal costs of irrigation water, where the firm is conceptualized as the producer of irrigation water, as influenced especially by fuel and labor costs, but also by design features of the irrigation system.
5. institutional features of the water supply system, including rules affecting when water can be pumped, how much can be diverted, and when it can be used, especially during water-short years.

The concentration in the literature has been on yield variability, as influenced by aboveground and belowground conditions.

Boggess et al., and Yaron and Strateener envisioned a multiple-objective function that included yield variability. Reducing this source of uncertainty is also seen as a major dimension of the objective function by English (see also English and Orlob), as well as by Schoney et al. Windsor and Chow (p. 32) note that "assessment of this reduced variability (from irrigation) should . . . be included in . . . model analysis."

Hall and Buras; Harris and Mapp; and Yaron and Strateener all recognized the influence of product price variability, but none included such variability in the analyses. Apparently no one has examined the impact of irrigation cost (water cost) variance on strategy.

Rhenals and Bras dealt specifically with aboveground conditions in the examination of ET uncertainty. English et al, were primarily concerned with belowground conditions, with the examination of a "filtering" technique for reducing the uncertainty in measurement of a signal (such as soil moisture) to start irrigation.

None of the authors examined institutional change or action as a possible source of uncertainty. Only Yaron and Strateener; Harris and Mapp; and Boggess et al. actually presented estimates of the variance of profits associated with various strategies and this only as related to yield variability. And only Boggess et al. and Yaron and Strateener suggested that the minimum variance, maximum profit strategy may be the most preferred by irrigation managers.

Directions for this Study

There appears, then, to be a considerable lack in our knowledge base regarding the role of random influences in choosing an optimal irrigation-scheduling program. Also, there has been little work examining the trade-offs between variance and profit. This paper quantifies the risks and returns associated with all the major sources of variability outlined above, except for institutional uncertainty,[2] and trade-offs are examined. Empirical results are generated for the maximization of utility, profit, yield, and the average response to water objectives.

ECONOMIC DECISION FRAMEWORK

The setting visualized for our irrigation manager is a standard decision problem consisting of three com-

[1] That is, the decision then becomes either to irrigate for maximum yield or not to irrigate at all. Thus, the maximum profit and maximum yield objectives suggest the same water level and application strategies, usually at the water level where crop transpiration (and possibly ET) is maximized.

[2] This is justified herein as water supply authorities have yet to institute water regulations in the soybean area of Florida. The problem of (water) institutional uncertainty is real in other parts of Florida, however, and also may be of concern in other states and regions. Thus, this type of uncertainty should not categorically be ignored as it has been in the literature to date.

ponents: (1) an objective or decision criterion, (2) a set of alternative choices, and (3) a set of costs and constraints which limit the choice set. It is assumed, additionally, that the decision-maker is faced with risky and uncertain events. The logic of the formulation is that in humid regions the agricultural irrigator not only has an economic demand for water, but must also generally operate his own water-supply (irrigation system) service with its concomitant investment and operation costs. The appropriate conceptual formulation must describe these demand and supply relationships for irrigation water and outline the decision calculus of the manager. This has been detailed elsewhere.[3]

Risk assessment of decision alternatives can be approached in several manners. One of the more common is the expected utility hypothesis in which decision-maker is assumed to maximize expected utility (Anderson, Jock et al.). Perhaps the most widely used application of expected utility is expected value-variance (E-V) analysis, in which expected utility is expressed as a function of the expected value and associated variance in returns. In essence, the expected value and variance of the decision alternatives are calculated and the decision-maker chooses from the efficient set based on his particular utility function. A second risk assessment approach revolves around probability theory. This approach defines risk to be the probability that the outcome of a particular decision takes on an undesired value (Pitt). The purpose of risk assessment then is to quantify risk so that different strategies or decisions can be compared. Both E-V analysis and risk assessment are used in this paper to evaluate the risks associated with alternative irrigation strategies.

MODEL AND METHODS

The economic analysis presented here utilizes a process simulation model of the soybean crop (Wilkerson et al.) that is sensitive to photosynthetically active radiation (PAR), daily temperature, and soil-water stress, as determined by a soil-water balance model (Jones and Smajstrla) to simulate the production surface. The simulation model is used as a computerized experimental plot in which numerous irrigation strategies can be evaluated over multiple weather years at a relatively low cost in terms of time and money. The simulation model is more flexible and provides more detailed results than would a statistically estimated production function. The usefulness of the model is obviously dependent upon the accuracy of the simulation model results. To test the validity of the model, field plot results from three years of irrigation experiments (Hammond et al., unpublished data) were compared to simulated results for the identical strategies and weather years (Figure 1). A comparison of simulated yield with observed yields indicated a correlation of 0.98. The two sets of data were independent in that the experimental data in the test set were not used in specifying the model parameters.

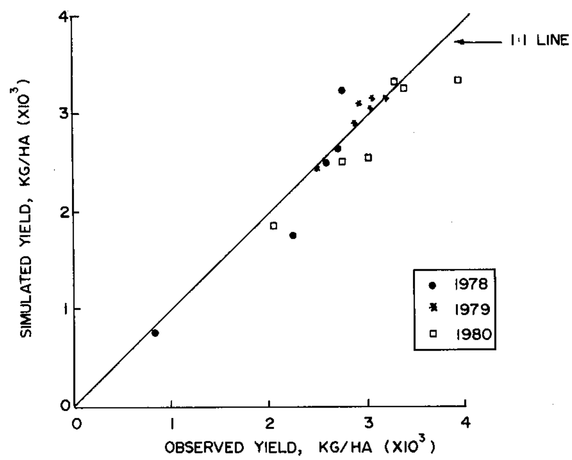

Figure 1. Comparison of Simulated to Observed Yields for Three Years of Experimental Data.

The crop-growth and soil-water models are controlled by a set of subroutines which include (1) interfaces to specify and update model parameters, (2) a multiyear driver that runs the simulation under 17 seasons of historical weather (temperature, rainfall, radiation, and pan evaporation) to obtain expected values and variances of yield and water variables, and (3) an economic and statistical subroutine which accumulates the results from different weather seasons and calculates the decision outcome. The model components are decribed in more detail in Swaney et al.

An irrigation cost generator (d'Almada et al.) was used to generate irrigation variable costs for a standard quarter section (54 hectare), medium-pressure (75 p.s.i.), center-pivot irrigation system. This system is common throughout the Great Plains sections of the western U.S., as well as in the Southeast. With a 1,000-gallon-per-minute pump, the system can make a full revolution applying one centimeter of water in a 24-hour period. Irrigation variable costs were developed by running the generator for all possible combinations of the variables giving the equation

$$(1) \quad IVC_t = [(5.834 - 0.101X + 0.0067X^2) + 3.5\,(P_d - 0.317)]\,W_t$$

where

IVC_t = per hectare irrigation variables costs in year t;
X = amount of irrigation water applied per application in centimeters;
P_d = price of diesel fuel in dollars per liter, fixed at \$0.317 for this analysis;
W_t = total irrigation water applied in year t in centimeters.

Other variable production costs (e.g., fertilizer and

[3] For those not familiar with the static, economic formulation of such a decision problem, see Lynne and Carriker.

pesticides) were assumed to increase 10 percent under irrigation relative to dryland soybeans. Thus, all the results herein apply to a 54-hectare field of soybeans under a center-pivot regime. Also, all other costs were ignored in the following analysis, thus giving a net return above variable irrigation costs. This is justified herein because the concern is for *intraseasonal* water allocation.[4] Fixed costs are of no concern, assuming this system type has already been chosen. The analyses of alternative systems is left for later studies.

Optimal Irrigation Timing and Amount. In order to determine the best parameters of the irrigation-scheduling strategy for various decision criteria, parameters were varied in a series of simulation runs. These parameters were amount per application (i_j) and level of soil moisture at which irrigation is applied or irrigation threshold (τ_j). The optimal values of the parameters can be obtained for a finite set by simply evaluating the relevant objective function for each pair and selecting the pair that results in the optimum value of that function. For this evaluation, the set of i's selected were the integer values 0 to 7 centimeters, inclusive. The set of τ's ranged from 0 to 100 percent in steps of 10 percent. Thus, a total of 88 pairs were simulated for the 17 seasons of historical weather. The expected value and standard deviation of yield, irrigation water applied, and energy use were calculated for each of the runs.

Variance Calculations. The problem at hand requires calculation and analysis of the variability in expected gross returns net of variable irrigation costs associated with alternative irrigation-scheduling decisions. These net returns (π) can be represented mathematically as

$$(2) \qquad \pi = py - rx$$

where p is the price of soybeans, y is the yield, r is the marginal cost of irrigation water per unit, x is the amount of irrigation water applied, and π, p, y, r, and x are all random variables. The variance in π can be calculated by two different methods. First, if sufficient random observations on π exist, the variance can be estimated directly from the observations. This approach, however, provides no information on the proportion of variance associated with each component of net returns. A second approach for calculating the variance of the returns that does allow partitioning of the variance among the components is to express it as a function of the variances of the random variables p, y, r, and x.

Equation (2) is a linear function of two product terms, py and rx. Burt and Finley present a procedure for expressing the variance of the product of two random variables as a linear function of the variance and covariance of the two random variables.[5] Using their procedure, the variance of return for a particular irrigation strategy can be expressed as

$$(3) \qquad \sigma^2_{\pi i} = (\bar{y}_i)^2\sigma^2_p + (\bar{p})^2\sigma^2_{yi} + (\bar{r})^2\sigma^2_{xi} + (\bar{x}_i)^2\sigma^2_r - 2\sigma_{pyi,rxi}$$

where σ^2_i is the variance in net returns for irrigation strategy i; $\bar{y}_i$ and $\sigma^2_{\bar{y}i}$ are the mean and variance of yield associated with the irrigation strategy i; $\bar{p}$ and σ^2_p are the mean and variance of soybean price; $\bar{r}$ and σ^2_r are the mean and variance of irrigation pumping cost per unit of water; $\bar{x}_i$ and σ_{xi} are the mean and variance of irrigation water applied for irrigation strategy i; and $\sigma_{pyi,rxi}$ is the covariance between py_i and rx_i.

Two statistical independence assumptions were used in deriving equation (3). First, it was assumed that for an individual farmer following a fixed irrigation strategy, yield and price are independent. Similarly, pumping costs per unit of water and irrigation water applied are assumed independent. This assumption is believed reasonable for a center-pivot irrigation system, given the extensive ground water available in most of the Southeast and the range of irrigation strategies evaluated.

Following Burt and Finley, the relative contribution of each component random variable to the variance of π can be analyzed by normalizing equation (3). The normalization procedure entails dividing by the sum of the individual variance components giving

$$(4) \qquad \frac{(\bar{y}_i)^2\sigma^2_p + (\bar{p})^2\sigma^2_{yi} + (\bar{r})^2\sigma^2_{xi} + (\bar{x}_i)^2\sigma^2_r - 2\sigma_{pyi,rxi}}{(\bar{y}_i)\sigma^2_p + (\bar{p})^2\sigma^2_{yi} + (\bar{r})^2\sigma^2_{xi} + (\bar{x}_i)^2\sigma^2_r} =$$

$$P_p + P_{yi} + P_{xi} + P_r - P_{pyi.rxi}$$

where each term on the right-hand side is the respective numerator term divided by the denominator.

Equations (3) and (4) require knowledge or estimates of the mean and variances of p, y_i, r, and x_i, and the covariance of pyi with rxi. The means and variances of y_i and x_i are derived from the simulation re-

[4] That is, this paper is designed to address only the intraseasonal decision questions. As pointed out by an anonymous referee, ignoring fixed costs can lead to an overestimate of irrigation returns in the Southeast. We cannot disagree. However, there are already large numbers of these centerpivot systems operating in the region, especially in Georgia and northern Florida. The results of this paper are especially relevant to those growers and irrigators.

[5] Briefly, if gross returns are expressed as the product of price and yield

$$g = py$$

then a Taylor's series expansion can be used to express g as

$$g = \overline{p}\,\overline{y} + (p - \bar{p})\bar{y} + (y - \bar{y})\bar{p} + (p - \bar{p})(y - \bar{y})$$

where p and y denote the means of p and y. Taking the expectation of both sides yields

$$E(g) = \overline{py} + Cov(p,y)$$

The variance of g then, using the latter two expressions, is

$$\begin{aligned} Var(g) = {} & E[g - E(g)]^2 \\ & (\bar{y})^2 Var(p) + (\bar{p})^2 Var(\bar{y}) + 2\overline{py}\, Cov(p,y) \\ & + E[p - \bar{p})(y - \bar{y}) - Cov(p,y)]^2 \\ & + 2\bar{p}\, E(p - \bar{p})(y - \bar{y})^2 \\ & + 2\bar{y}\, E(p - \bar{p})^2(y - \bar{y}) \end{aligned}$$

If p and y are stochastically independent then their covariance equals zero and the last four terms of the last expression will be zero. A similar expression was developed for rx to give equation (3) sults, with those of p and r calculated from historical price series (USDA, SRS).

Season average prices of soybeans for the period 1960 to 1980 were converted to 1981 dollars using the "All Farm Products Prices Received by Farmers Index" (USDA, SRS). The inflated price series was then corrected for a linear trend and the variance in the series around the trend line calculated.

A similar approach was used to estimate the variance in irrigation water costs. Since water costs are a linear function of fuel prices, equation (1), diesel fuel prices were obtained for the period 1960 to 1980. These prices were converted to 1981 dollars using the "Production Items, Taxes, Interest, and Wage Rate Prices Paid by Farmers Index" (USDA, SRS). The inflated fuel price series was corrected for a linear trend and the variance in the series around the trend line calculated.

The covariance between pyi and rxi was obtained for each strategy i by determining p_jy_{ij} and r_jx_{ij} for each of the 17 years (j = 1 to 17) of weather and price data. The covariance between the two vectors, gross returns and variable irrigation costs, was then calculated for each of the strategies.

RESULTS

The simulations produced a net-return response surface in the variables irrigation threshold (τ) and amount per application (i) (Figure 2). Maximum net returns occur at a value of 70 percent of field capacity as the threshold and a 1-cm application per irrigation. This combination results in an expected net return of approximately $553 per hectare (Figure 2), compared to $334 for soybeans produced without irrigation.

The simulated crop undergoes water stress whenever soil water drops below 80 percent of water-holding capacity. Thus, the maximum net-returns strategy allows some stress to the crop, as expected, since the marginal cost of irrigation exceeds the marginal value of the increase in yield as irrigation is increased to reduce stress. At the 70 percent threshold, 2 cm of the 7 cm of water available in the profile have been depleted. The 70 percent and 1 cm strategy replaces only 0.75 cm (assuming a normal operating efficiency for the center-pivot system) of the deficit. In all cases, return-maximizing strategies for each of the irrigation threshold levels leave some capacity for additional water storage after irrigation. Given the frequency, magnitude, and inherent uncertainty of rainfall in humid areas, an irrigation strategy is desired that does not completely refill the soil profile but leaves some capacity for storage of rainwater. Otherwise, deep percolation and runoff increase at an economic cost to the producer. However, if one's objective is to maximize yield, the analysis indicates that the profile should be completely refilled whenever the available soil water drops to 80 percent of that available at field capacity. While not shown in Figure 2, the maximum yield objective is realized with values of 1 cm per application and the 90-percent threshold. At this combination the expected yield per hectare is 123 kg greater than the maximum returns strategy, but expected net returns per hectare are $258 lower (Table 1).

A third possible criterion for scheduling irrigation is to maximize average yield response per unit of irrigation water. A 50 percent threshold and 2-cm-per-application strategy maximizes average yield response (yield response divided by water applied in Table 1). This strategy uses on the average only 40 percent as much irrigation water as the maximum returns strategy. However, the expected yield is approximately 505 kg lower and expected net returns $58 lower (Table 1) than the maximum returns situation.

E-V Analysis Results. Expected net returns and standard deviations of net returns for 11 alternative irrigation strategies are reported in Table 1. As indicated earlier, the 70 percent and 1 cm strategy maximizes expected net returns. However, a 50-percent and 3-cm strategy minimizes the standard deviation of net returns. A comparison of these strategies with the other strategies indicates that the 50-percent and 3-cm strategy dominates all strategies with thresholds lower than 50 percent and that the 70-percent and 2-cm strategy dominates all strategies with thresholds higher than 70 percent. This translates graphically to a "loop" in E-V space (Figure 3).

The explanation for this loop is imbedded in the proportion of net returns variance attributable to the various component random variables (Table 1). Since irrigation water reduces yield variability, the proportion of total variability attributable to yield variation declines as irrigation frequency increases (in equation (4) $\sigma^2_{\bar{y}i}$ declines and $\bar{p}$ remains constant). Conversely, the proportion of total variability attributable to price and pumping cost increases. The output price component increases as the irrigation threshold increases from 0 to 70 percent, since $\bar{y}$ increases and σ^2_p

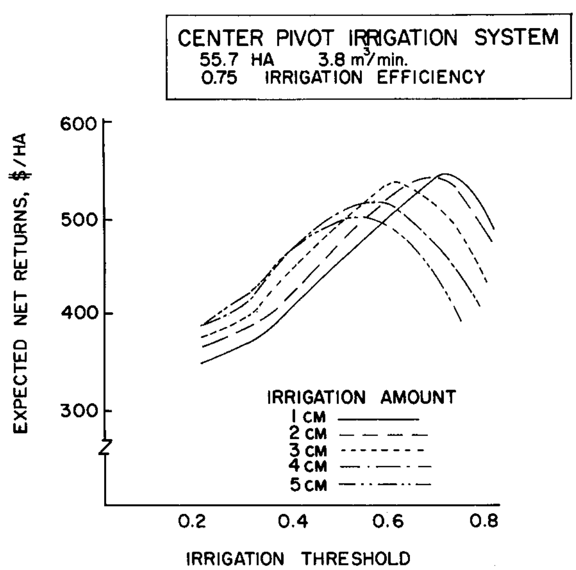

Figure 2. Simulated Net Returns Above Variable Irrigation Costs as Related to Irrigation Threshold and Water Application Rate per Hectare, Soybeans.

Table 1. Expected Net Returns, Yields, Water Applied, Standard Deviation of Net Returns, and Proportion of Net Returns Variance by Components for Alternative Irrigation Strategies.

	Proportion of Net Returns Variance								
Strategy[a]	Price	Water Yield	Irrigation Cost	Water	Deviation Covariance[b] ($)	Standard Expected Net Returns ($)	Yield Net Returns ($)	Water Response[c] (Kg/ha)	Applied[d] (cm)
0,0	0.29	0.71	0.0	0.0	0.0	238.59	344.25	0	0.0
30,6	0.63	0.36	0.0	0.01	-591.79	189.85	427.60	466	6.7
50,2	0.82	0.16	0.0	0.02	-715.08	180.24	495.55	782	8.8
50,3	0.87	0.12	0.0	0.01	-188.64	179.48	509.62	876	10.8
50,4	0.89	0.08	0.0	0.02	-207.76	180.28	513.29	945	13.4
60,2	0.93	0.05	0.0	0.02	- 23.33	179.90	530.87	1038	14.2
60,3	0.94	0.04	0.01	0.02	167.65	182.09	539.87	1128	16.9
70,1	0.96	0.02	0.01	0.01	403.79	186.00	553.36	1287	21.3
70,2	0.96	0.02	0.01	0.01	370.29	185.65	544.36	1289	22.9
80,1	0.94	0.02	0.03	0.01	810.36	190.46	488.60	1394	37.4
90,1	0.88	0.02	0.09	0.02	1498.28	194.53	295.38	1410	71.8

[a] Percent soil water remaining when irrigation is initiated and centimeters of water applied per application.
[b] Covariance between gross returns and variable irrigation (water) costs.
[c] Average yield response to irrigation in kilograms per hectare.
[d] Average total seasonal irrigation in centimeters.

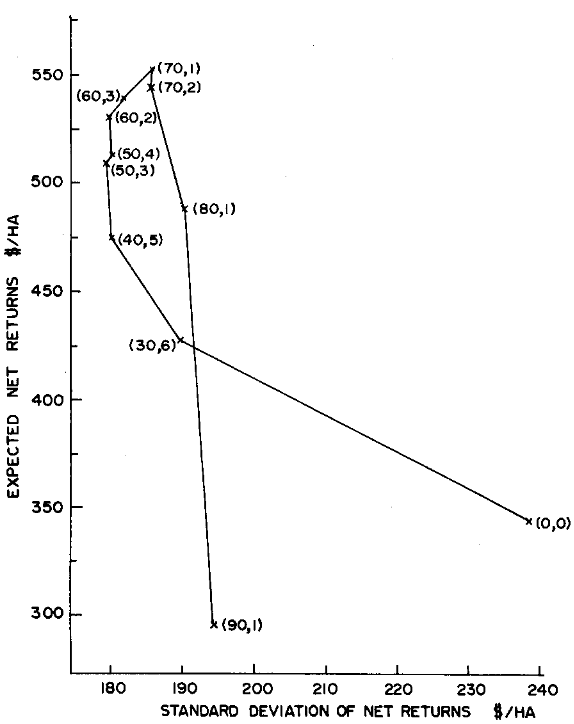

Figure 3. Plot of Expected Net Returns Versus Standard Deviation (Price, Yield, Pumping Cost, and Irrigation Water Applied all Random Variables).

is constant as irrigation frequency increases, equation (4). For thresholds greater than 70 percent, yields level off, despite a rapid increase in water applied. As a result, the price-variability component declines and the pumping-cost component increases. At low levels of irrigation, the reduction in yield variability dominates the increased variability in price and pumping cost; thus, total variability declines. As the frequency of irrigation increases, the decline in yield variability slows, and the increased variability in the other components dominates, causing total variability to rise.

The covariance between gross returns and variable irrigation (water) costs is negative for low thresholds and positive for high thresholds (Table 1). While this result does not affect the general shape of the E-V graphs, the reason behind the increasing trend in the covariance are informative. For low-frequency strategies, drought damage to the crop has occurred before the threshold is reached, and the water applied is relatively ineffective. Since the low thresholds are reached more often in dry years than in wet years, there is a tendency for low yields to be accompanied by relatively large applications of irrigation water and vice versa. As the threshold level is increased, less stress occurs before irrigation is initiated. As a result, the irrigation water is more effective. At the higher thresholds, irrigation is more frequent, stress is reduced, and yields are greater.

Probability Curve Analysis of Irrigation Strategies. The risk-return information in Figure 3 can alternatively be represented as curves in which return is plotted against probability of exceeding net return (Palmer). This is accomplished by ordering the 17 yearly observations for each strategy on the basis of expected net returns and calculating the corresponding cumulative probability. If the underlying distributions are normal, these pairs will plot as straight lines on normal probability paper.

Probability curves for five alternative irrigation strategies are plotted in Figure 4. The resulting curves indicate that the underlying distributions may approximate normal distributions.[6] Notice that no single strategy dominates the other four. The 70-percent and 1-cm strategy does dominate the no-irrigation (0,0) and the 80-percent and 1-cm strategies. The 70-percent and 1-cm strategy also outperforms the 50-percent and 4-cm and the 60-percent and 3-cm strategies at income levels above the mean. However, in 3 years out of 10, no irrigation results in a higher return over variable costs than the 80-percent and 1-cm strategy.

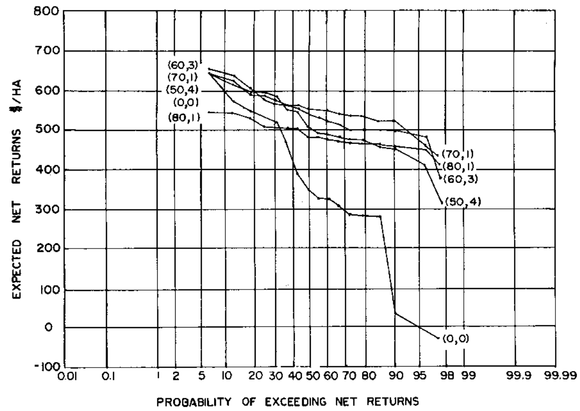

Figure 4. Probability Curves for Five Alternative Irrigation Strategies.

SUMMARY AND CONCLUSIONS

A review of the irrigation-scheduling literature revealed that mainly single-dimensional decision criterion had been used to determine optimal strategies (maximum yield, maximum profit, minimal water for a fixed level of ET, maximum yield obtainable with a fixed quantity of water, etc.). Also surprisingly, only 3 of the approximately 50 studies examined considered the risk implications of irrigation. In humid regions, one of the primary attractions of irrigation is that it reduces yield variability. In this study, a process simulation model was used to analyze the impact of alternative irrigation strategies on producers' risks and net returns above variable irrigation costs. The results for several objectives—maximum net returns, maximum yield, and maximum return per unit of irrigation water—were identified. The E-V frontier for alternative irrigation strategies was determined and the total variability in net returns above the variable costs was partitioned between applied components of price, yield, pumping costs, and irrigation water. This will facilitate the use of utility considerations to select the appropriate points.

The results indicate that optimal irrigation strategies in humid areas call for more frequent applications with smaller rates than would generally be recommended in arid regions. The results also indicate that given the uncertainty of rainfall in humid regions, incomplete wetting of the depleted profile maximizes net returns.

A breakdown of net-returns variance into its component parts indicated that the relative importance of yield variability declines significantly, and the relative importance of price variability increases significantly as irrigation frequency increases. Variability in pumping costs and amount of irrigation water applied are insignificant, except at extremely high irrigation frequencies. The covariance between gross returns and variable irrigation costs, though relatively insignificant, is negative for low-frequency irrigation strategies and positive for high-frequency irrigation strategies.

If price variability exists, risk averse irrigators may choose to irrigate less frequently than the maximum net-return strategy, which dominated all strategies calling for more frequent applications. With both price and yield variability present, the maximum-yield irrigation strategy also maximizes the variance in net returns compared to all other irrigation strategies analyzed. If only yield variability is considered, the maximum yield irrigation strategy minimizes the variance in net returns.

These results suggest that decision rules for scheduling irrigation may be quite different in humid regions from those in arid regions and that the risk implications of irrigation are important. The key difference is the identified need to retain a water storage capacity in the soil to more effectively use rainfall during the growing season. This is not generally necessary in arid regions. In effect, significant uncertainty is introduced by rainfall events in humid regions. Additional research is needed to extend the analysis to additional crops, combinations of crops, and the impact of irrigation on total firm income and risk. The latter concern should be addressed in a suitable irrigation investment analysis that considers the longer-run dimension.

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[6] Seventeen observations are probably too few to adequately specify the underlying distribution. As with any estimation problem, confidence in the results increases as the number of observations increases. However, even with less than the "desired" number of observations, probability curves are a useful technique for displaying whatever risk information is contained in the observations.

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